

Neutrino Astro-Particle Physics

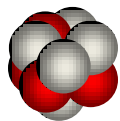
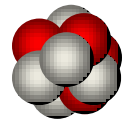
Maarten de Jong

Nikhef/Leiden

2011

What is a neutrino?

Radioactive decay (~1920)

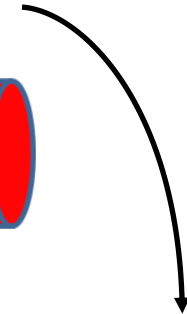
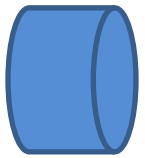


+



electron

magnet

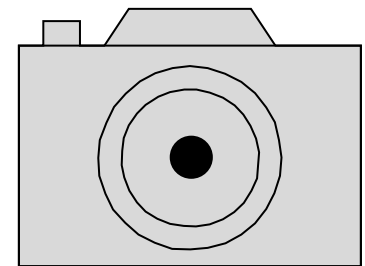


2-particle decay?



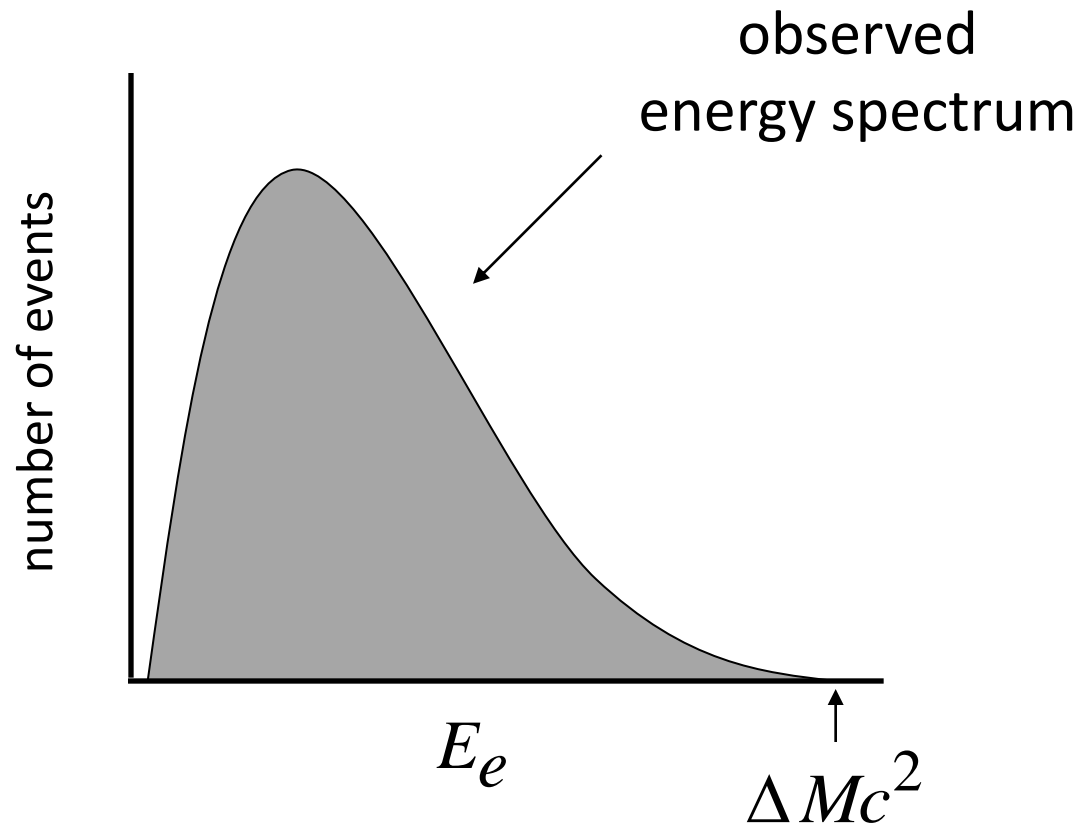
Einstein:

$$E_e = \Delta M c^2$$



detector

Radioactive decay (II)



Energy not conserved?

Original - Autograph of 744 0195
 Abschrift/15.12.30 74

Offener Brief an die Gruppe der Radioaktiven bei der
 Gouvernements-Tagung zu Tübingen.

Abschrift
 Physikalisches Institut
 der kgl. Technischen Hochschule
 Zürich

Zürich, 4. Dec. 1930
 Claristrasse

Lieber Radioaktive Damen und Herren,

Wie der Überbringer dieser Zeilen, den ich halbweltlich
 anzuhören bitte, Ihnen das obigen auseinanderzusetzen wird, bin ich
 angesichts der "falschen" Statistik der α - und β -Kerne, sowie
 des kontinuierlichen β -Spektrums auf einen verheissenen Ausweg
 verfallen: um den "Neutronen" (1) der Statistik und den Energieverlust
 zu retten. Nämlich die Möglichkeit, zu einem elektrisch neutralen
 Teilchen, die ich Neutronen nennen will, in den Kernen anzunehmen,
 welche dem Licht $1/2$ haben und das Anschliessungsprinzip befolgen und
 sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie
 nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen
 dürfte von derselben Grössenordnung wie die Elektronenmasse sein und
 jedenfalls nicht grösser als 0,01 Protonenmasse. Das kontinuierliche
 β -Spektrum wäre dann verständlich über der Annahme, dass beim
 Zerfall ein Neutron zerfällt und ein Elektron emittiert
 wird. Daraus, dass die Masse der Neutronen von Neutronen und Elektronen
 verschieden ist.

Man handelt es sich weiter darum, welche Kräfte auf die
 Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint
 mir aus wellenmechanischen Gründen (näheres weiss der Überbringer
 dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein
 magnetischer Dipol von einem gewissen Moment ist. Die Experimente
 verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons
 nicht grösser sein kann, als die eines gamma-Strahls und darf denn
 auch wohl nicht grösser sein als $\approx 10^{13}$ es).

Ich kann mich vorstellen aber nicht, dass über diese Idee
 zu diskutieren und werde mich erst vertrauensvoll an Sie, liebe
 Radioaktive, mit der Frage, wie es um den experimentellen Nachweis
 eines solchen Neutrons stünde, wenn dieses ein ebensolches oder etwa
 ideal grösseres Durchdringungsvermögen besitzen würde, wie ein
 gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein
 wenig wahrscheinlich aussieht und will von die Neutronen, wenn
 sie existieren, wohl schon längst gesehen hätte. Aber nur wer weiß,
 wann und der Ernst der Situation beim kontinuierlichen β -Spektrum
 wird durch einen Ausbruch meines verstorbenen Vorgängers in Ate,
 Herrn Debye, beleuchtet, der mir nämlich in Dresden gesagt hat:
 "O, daran soll man am besten gar nicht denken, sowie an die neuen
 Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.
 Aber lieber Radioaktive, denken und schreiben. Leider kann ich nicht
 persönlich in Tübingen erscheinen, da ich in Folge eines in der Nacht
 vom 6. zum 7. Dec. in Zürich stattfindenden Falles hier unerbittlich
 bin. - Mit vielen Grüssen an Sie, sowie an Herrn Neut, Ihren
 unterfertigter Diener

gn. W. Pauli

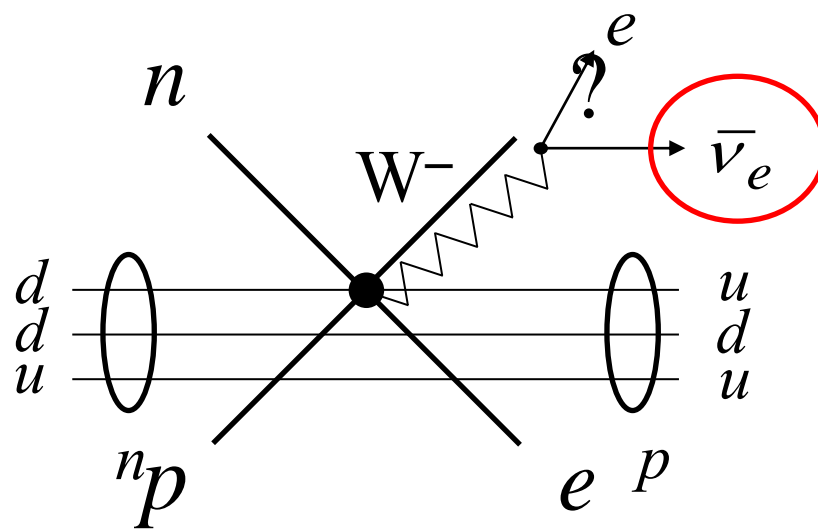
- Dear radioactive ladies and gentlemen,
- I may have found a solution to the energy crisis in radioactive decays.
- ... the existence of electrically neutral particles –which I call neutrons– in the atomic nucleus.
- The measured spectrum can be understood if such a neutral particle escapes together with the electron such that the total energy is conserved.
- But until now I did not dare to publish this idea and I ask you –radioactive people– whether it is possible to detect this particle experimentally.
- I admit that this idea is unlikely because the neutrons –if they exist– would have been found already.
- So, dear radioactive people, think about this idea and judge.

Pauli (1930): $n \rightarrow p + e + \bar{\nu}_e$

Fermi:

Theory of weak interaction

neutrino



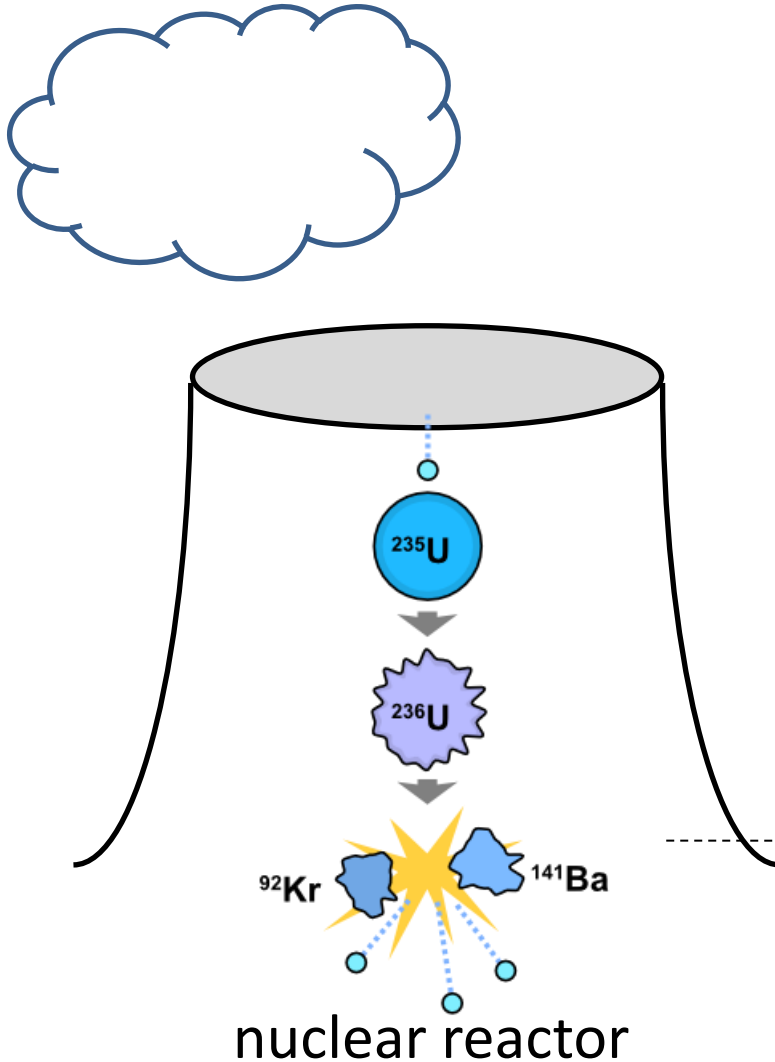
Feynman diagram

1950 – Reines & Cowan

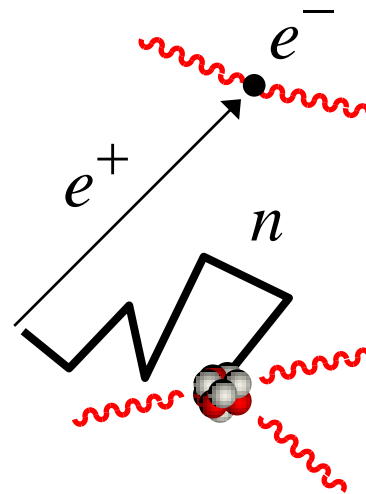
“Poltergeist”, Savannah River



Experimental evidence
existence of neutrinos



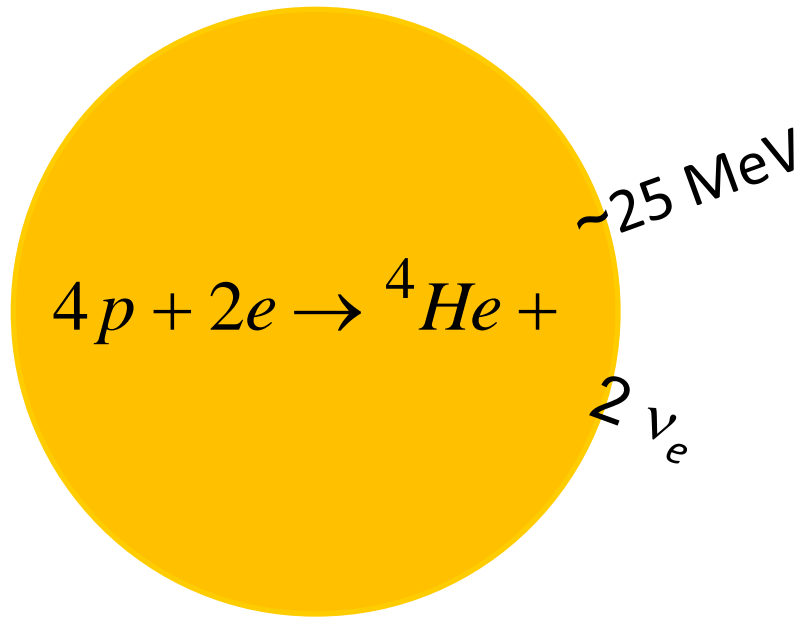
$\bar{\nu}_e$





Neutrino
astronomy

Sun



Light yield

$$L_{\square} = 3.92 \times 10^{26} \text{ W}$$

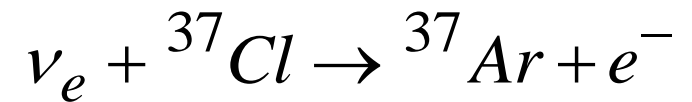
neutrinos

$$N_{\nu_e} = 2 \frac{L_{\square}}{1.6 \times 10^{-13} \times 25 \text{ MeV}} \approx 1.8 \times 10^{38} \text{ s}^{-1}$$

Homestake gold mine (USA)



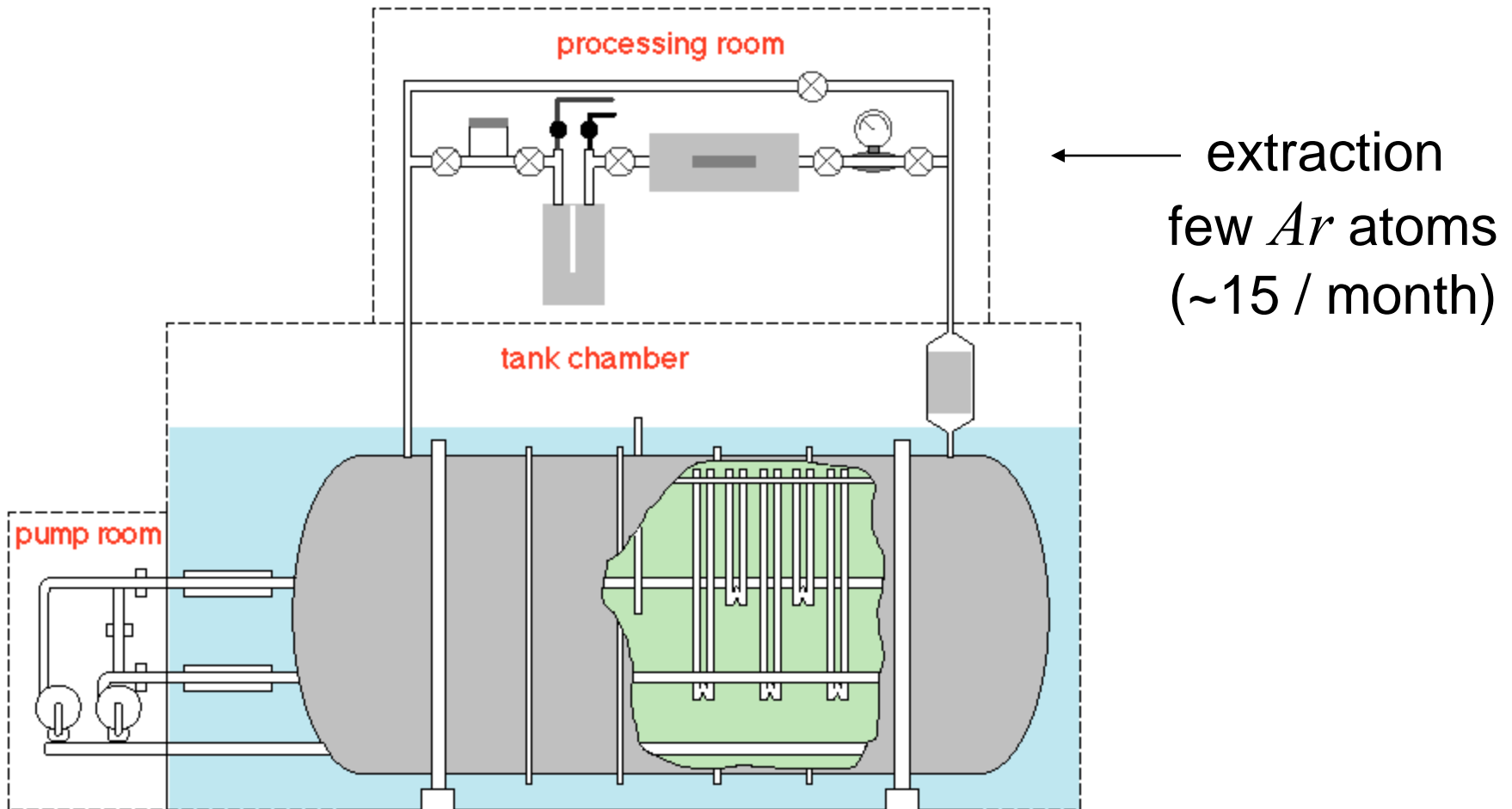
“inverse decay”



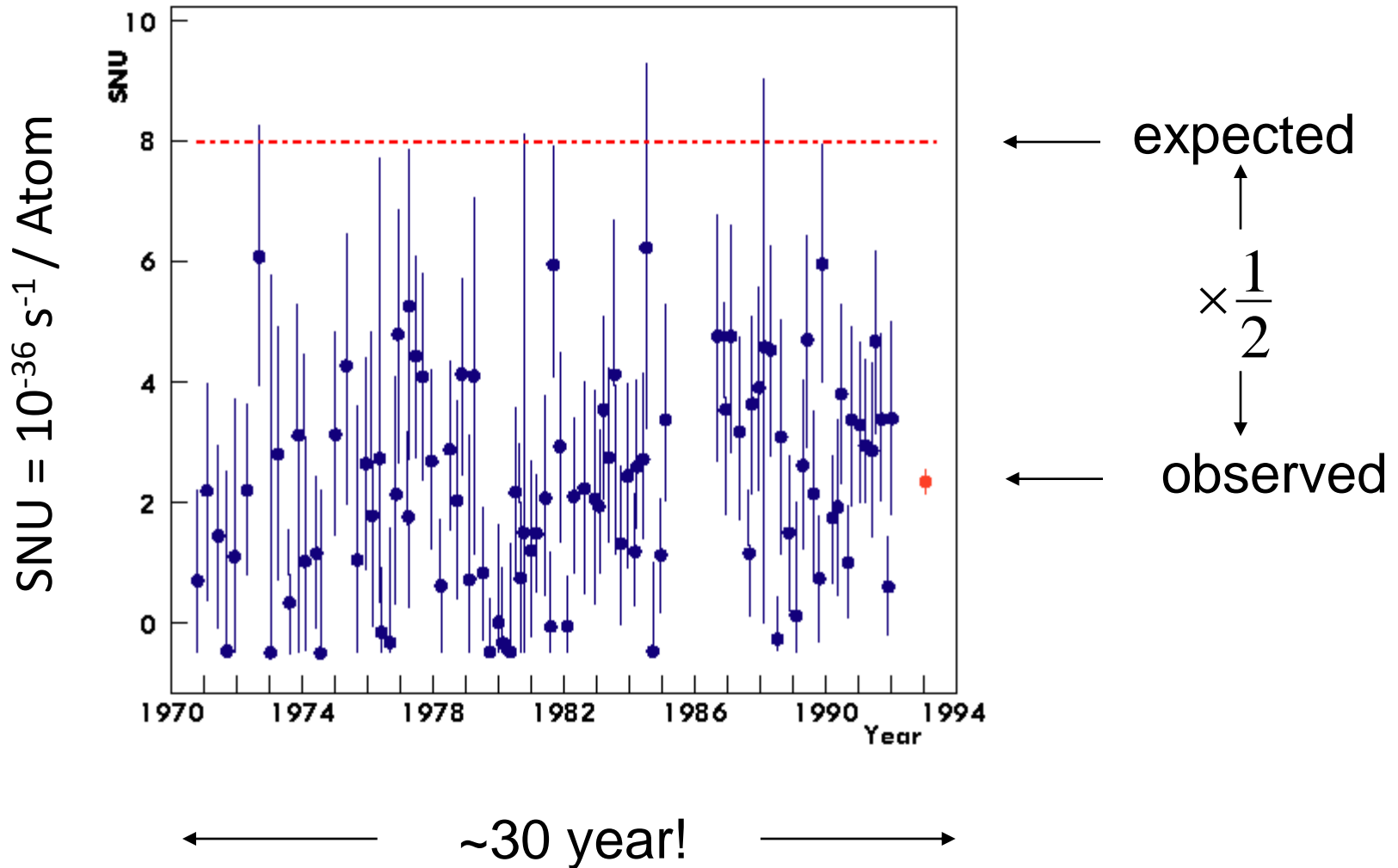
130 ton Chlorine

$$E_{\nu_e} \geq 0.814 \text{ MeV}$$

detection principle



Neutrinos from the sun

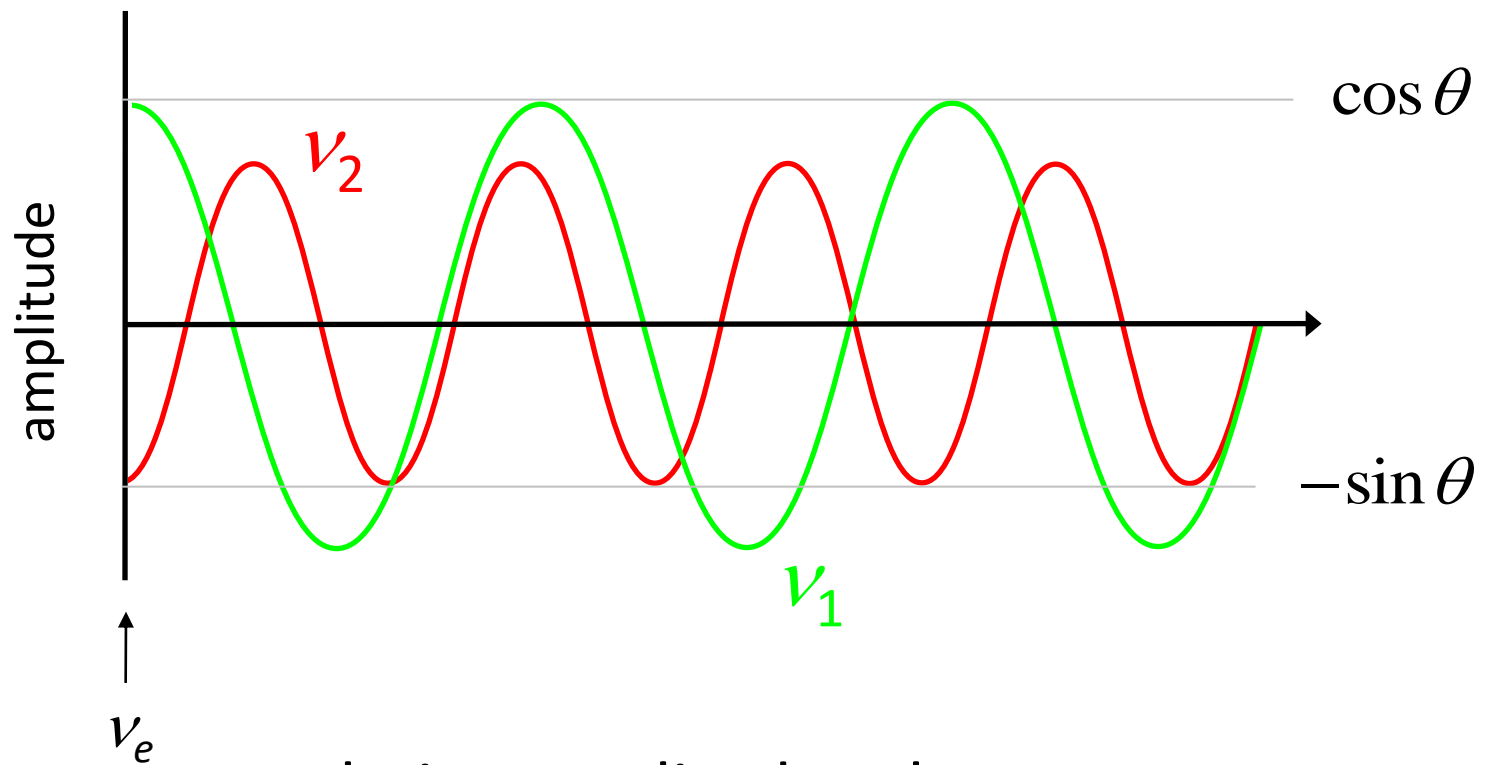


Observe $\frac{1}{2}$ neutrinos from the sun



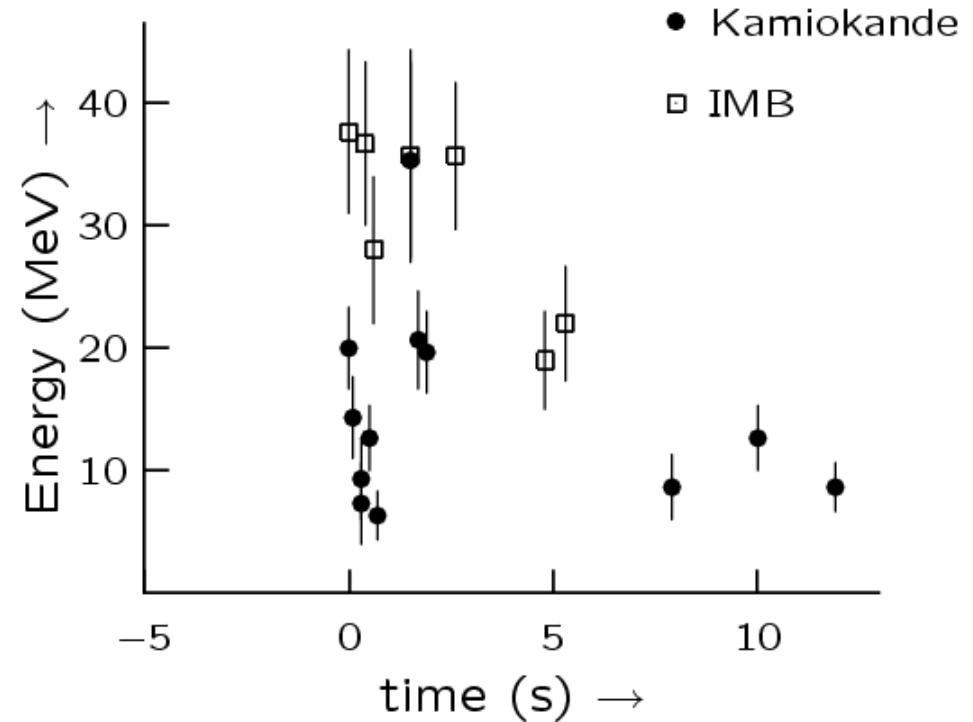
neutrino oscillations

Travelling of neutrinos through space



relative amplitudes change
as a function of time or distance

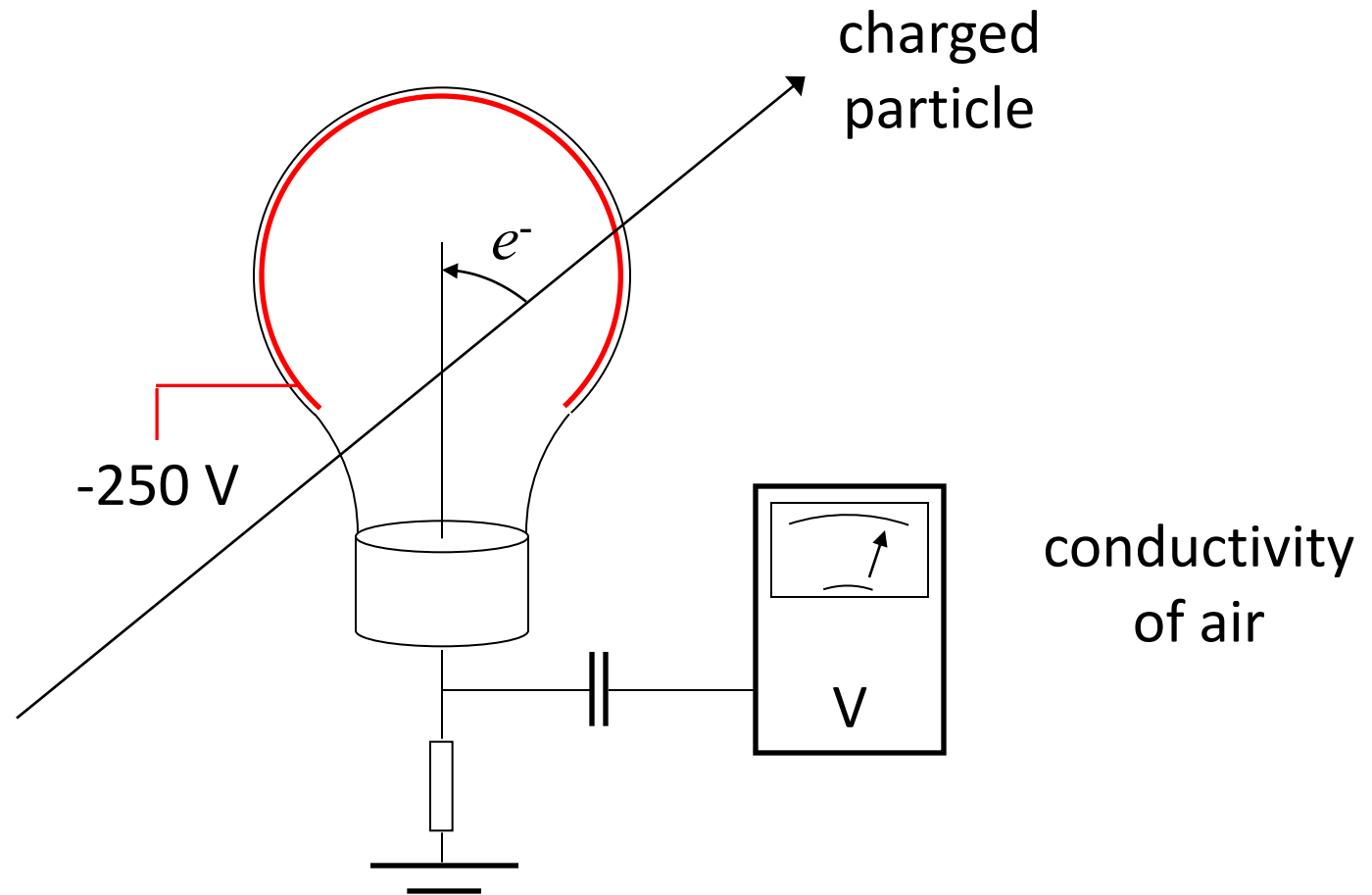
23 February 1987



Thermal neutrinos from Supernova (□ 99% of energy!)

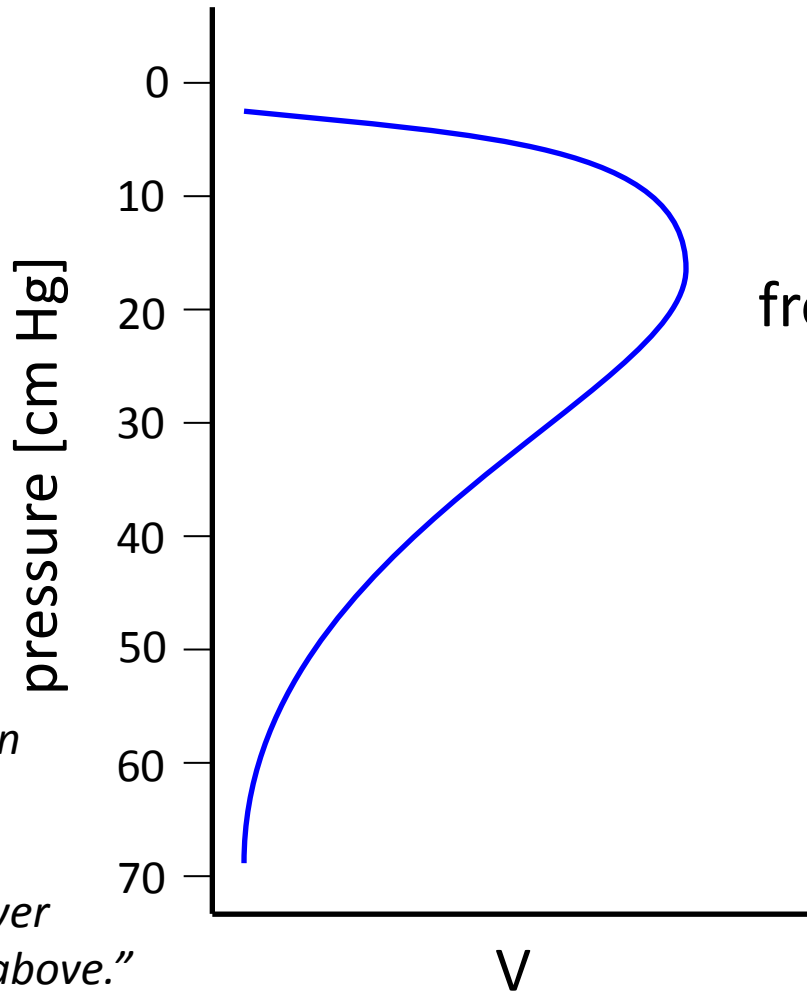
Why high-energy neutrino
astronomy?

Ionisation chamber (~1910)

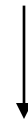


Earth' radioactivity?

V. Hess (1912)



radiation
from outer space!



cosmic rays

*“The results of my observation
are best explained by the
assumption that a radiation
of very great penetrating power
enters our atmosphere from above.”*

Earth

P. Auger (1938)

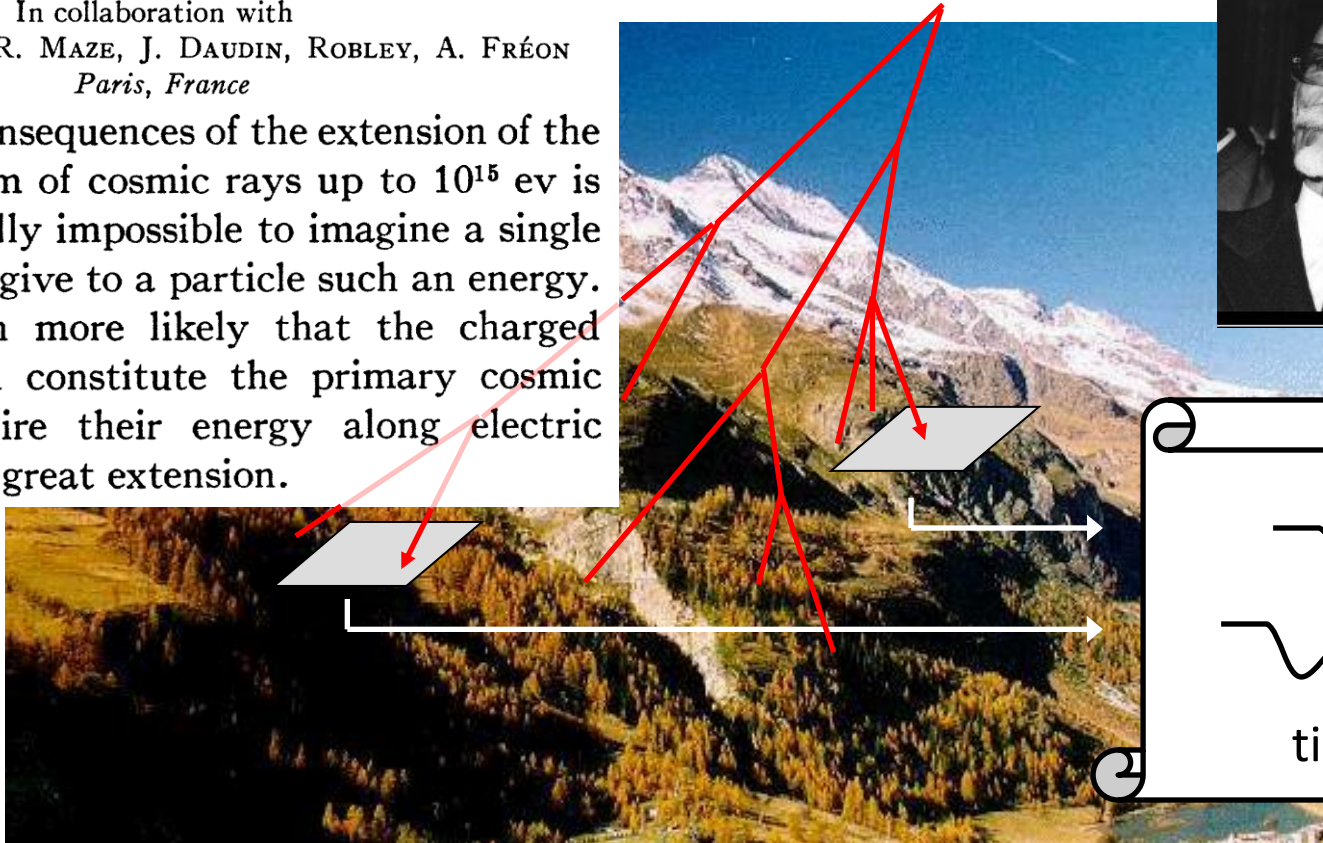
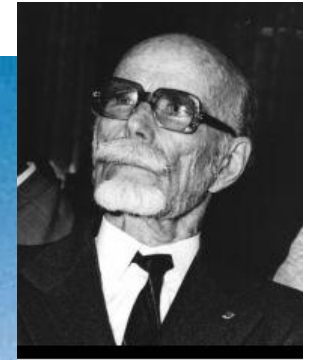
Extensive Cosmic-Ray Showers

PIERRE AUGER

In collaboration with

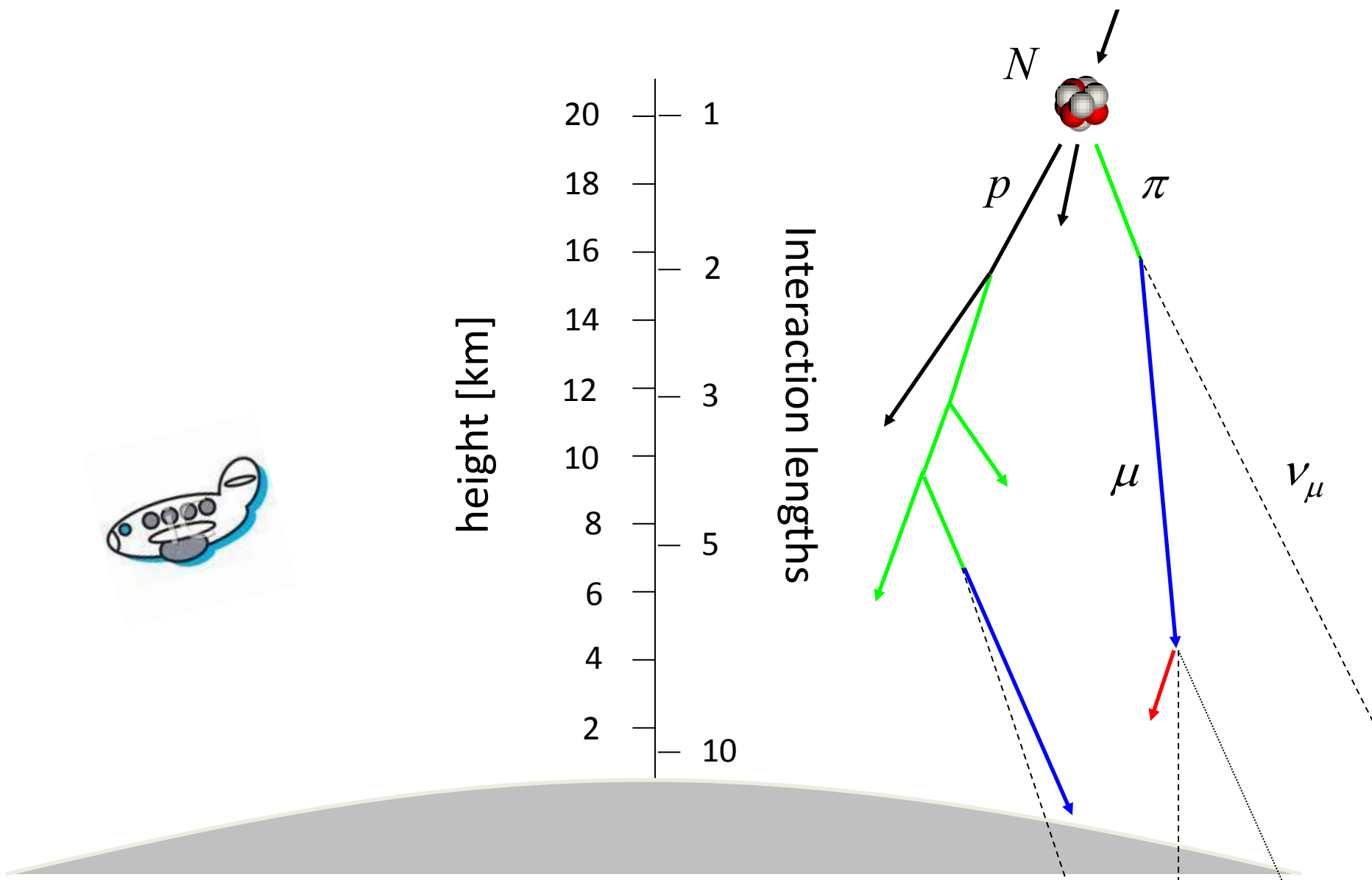
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France

One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} eV is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.

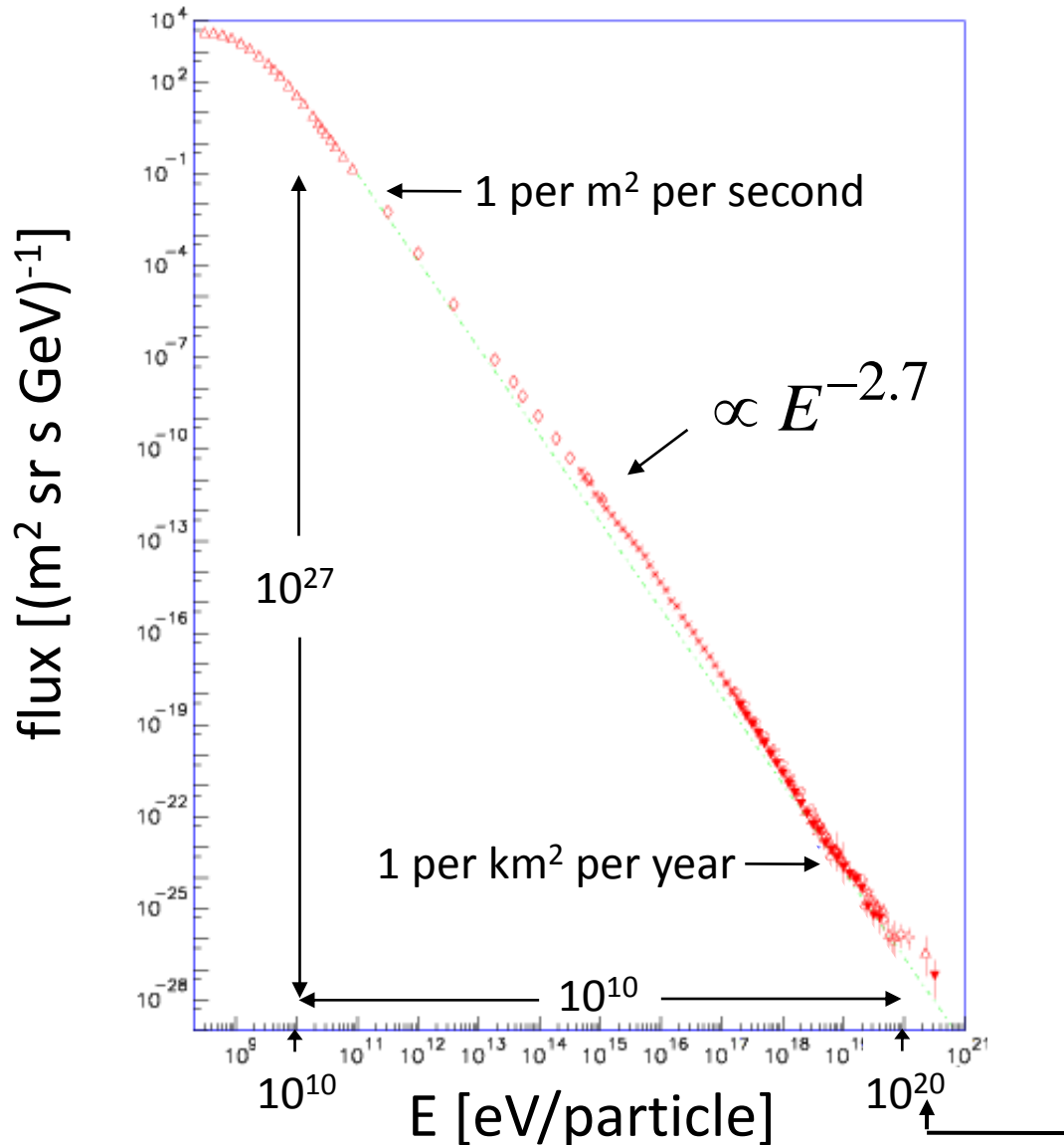


“Astrophysical particle acceleration”

Atmosphere seen by cosmic rays



Energy spectrum



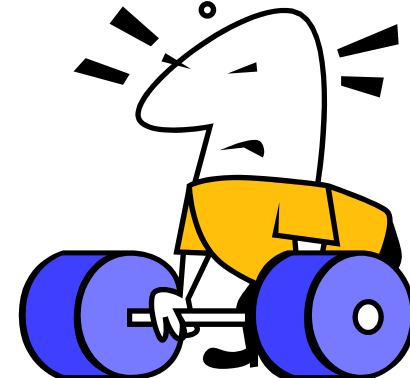
1.5 eV =



$N_A \approx 6 \times 10^{23}$?

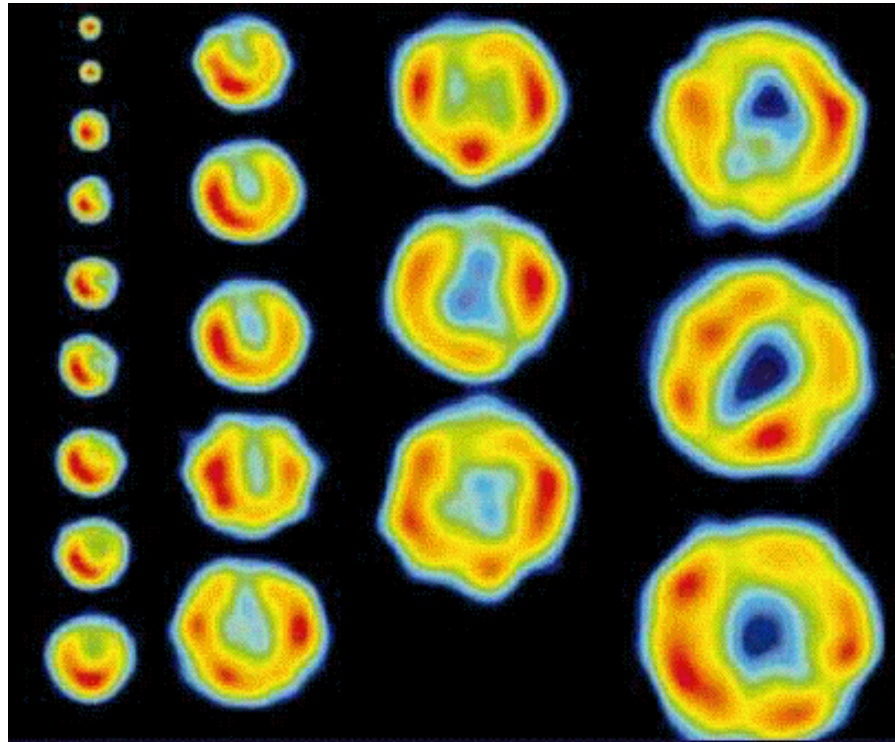
1 m

1 kg



SN1993J – M81

initial
expansion speed
~ 20000 km/s

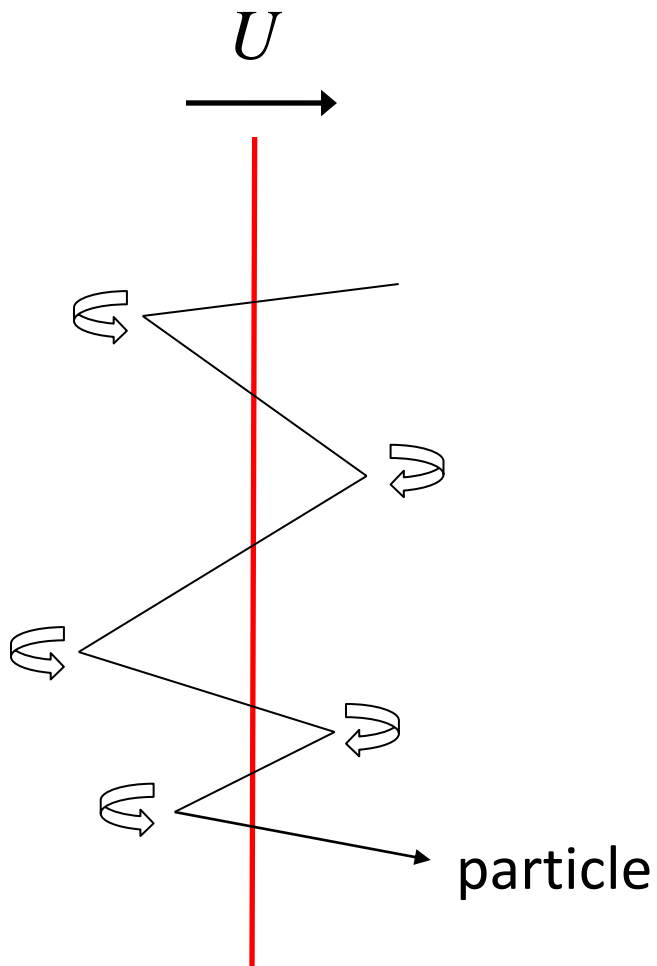


What you see:

The heating of cold interstellar gas by the expansion of a Super Nova shell

radio maps April 1993–June 1998

Fermi shock acceleration



Simple model

Acceleration $\Delta E = \alpha E$

Probability $P = \beta$



k steps $E = E_0 (1 + \alpha)^k$

$N = N_0 (\beta)^k$

Energy spectrum

$$\frac{\ln(N/N_0)}{\ln(E/E_0)} = \frac{\ln(\beta)}{\ln(1+\alpha)}$$

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\frac{\ln(\beta)}{\ln(1+\alpha)}}$$

$$\frac{dN}{dE} \propto E^{\frac{\ln(\beta)}{\ln(1+\alpha)} - 1} = E^{-2} \quad \square \quad \text{Observed spectrum}$$

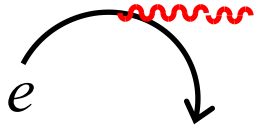
Thermodynamics

Relativity

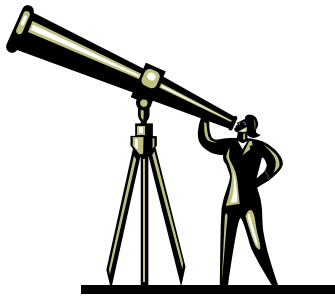
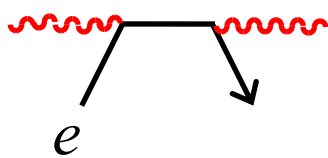
Which particles?

electrons

Synchrotron radiation

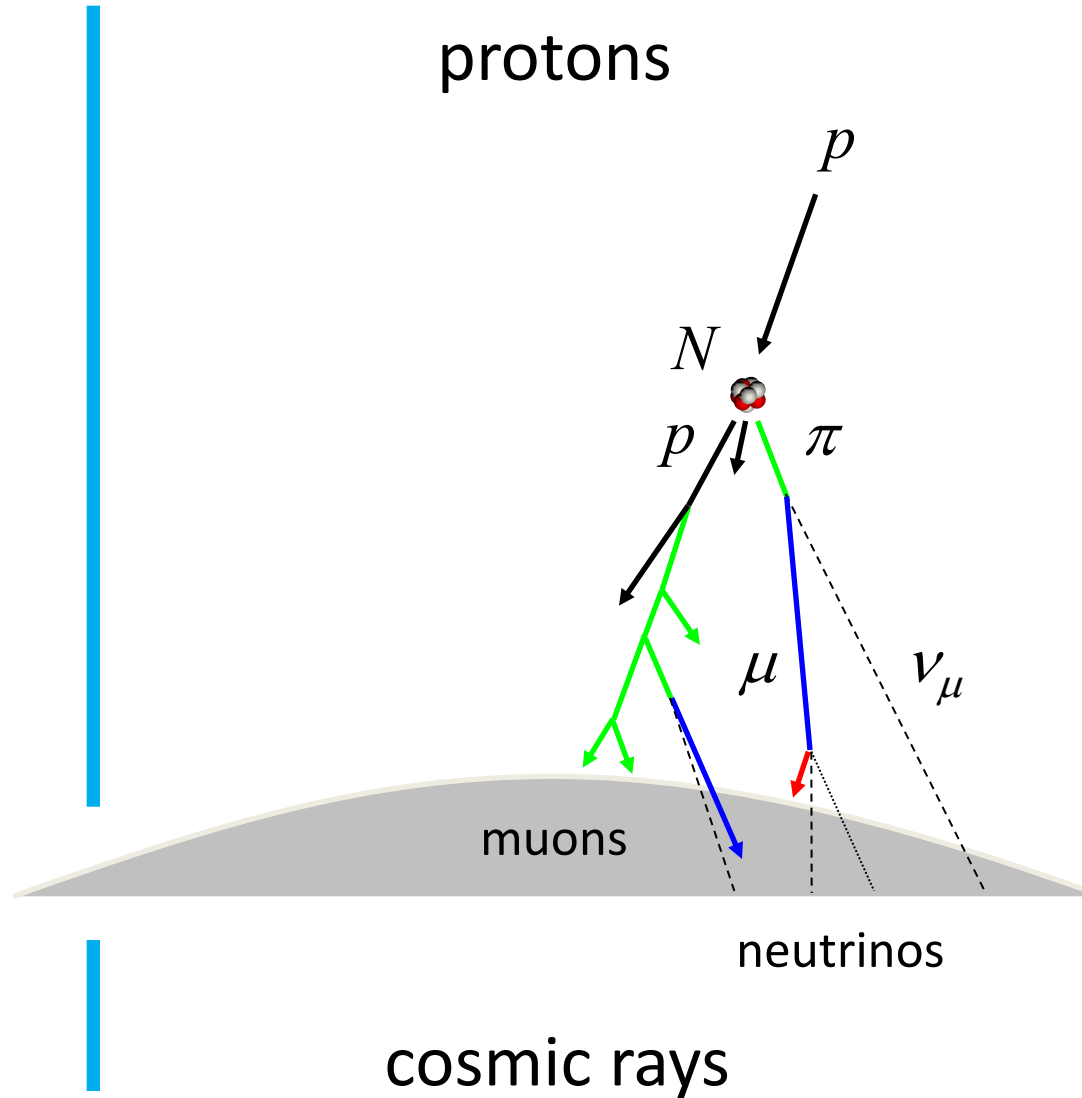


inverse Compton scattering



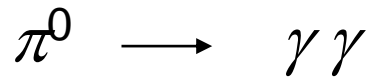
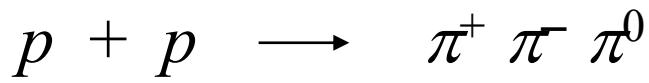
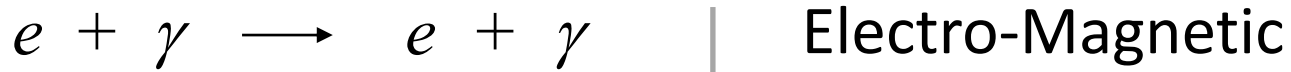
astronomy

protons

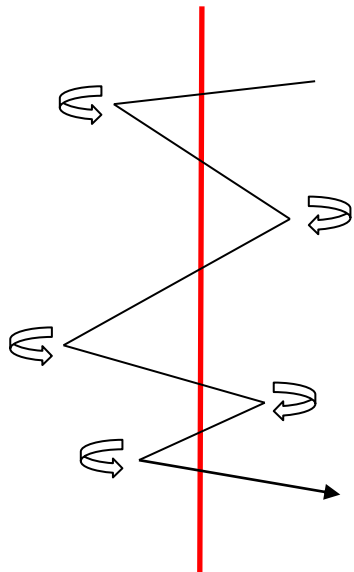


cosmic rays

Multi-messenger astronomy

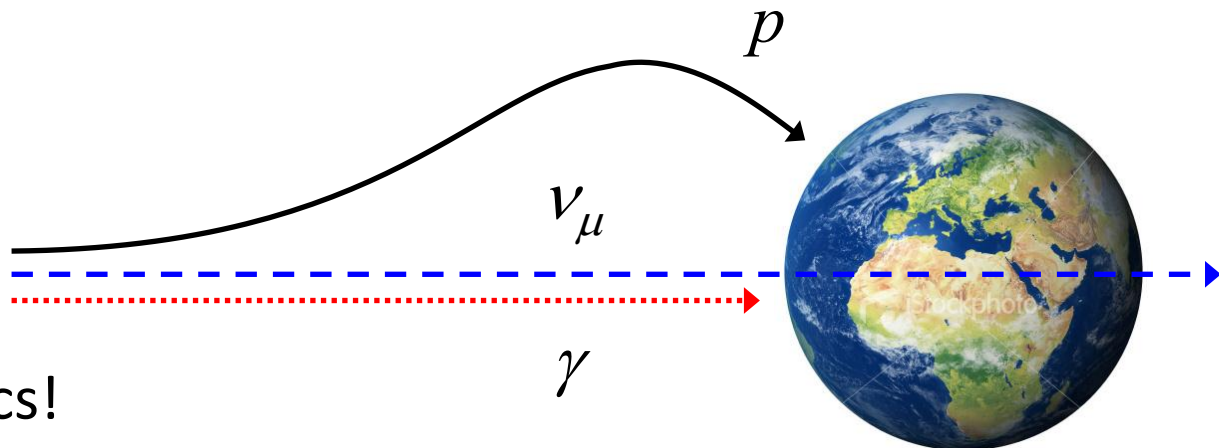


Hadronic



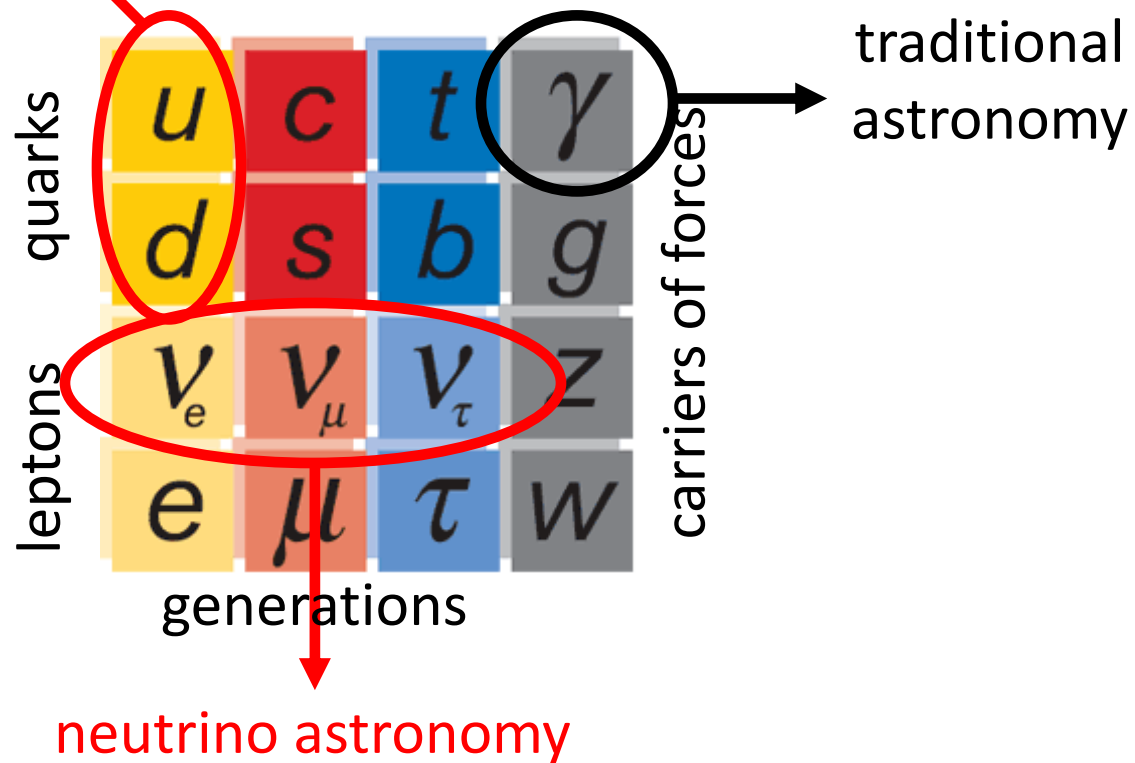
?

particle physics!



Astro-particle physics

cosmic rays
(consist of
u en d quarks)



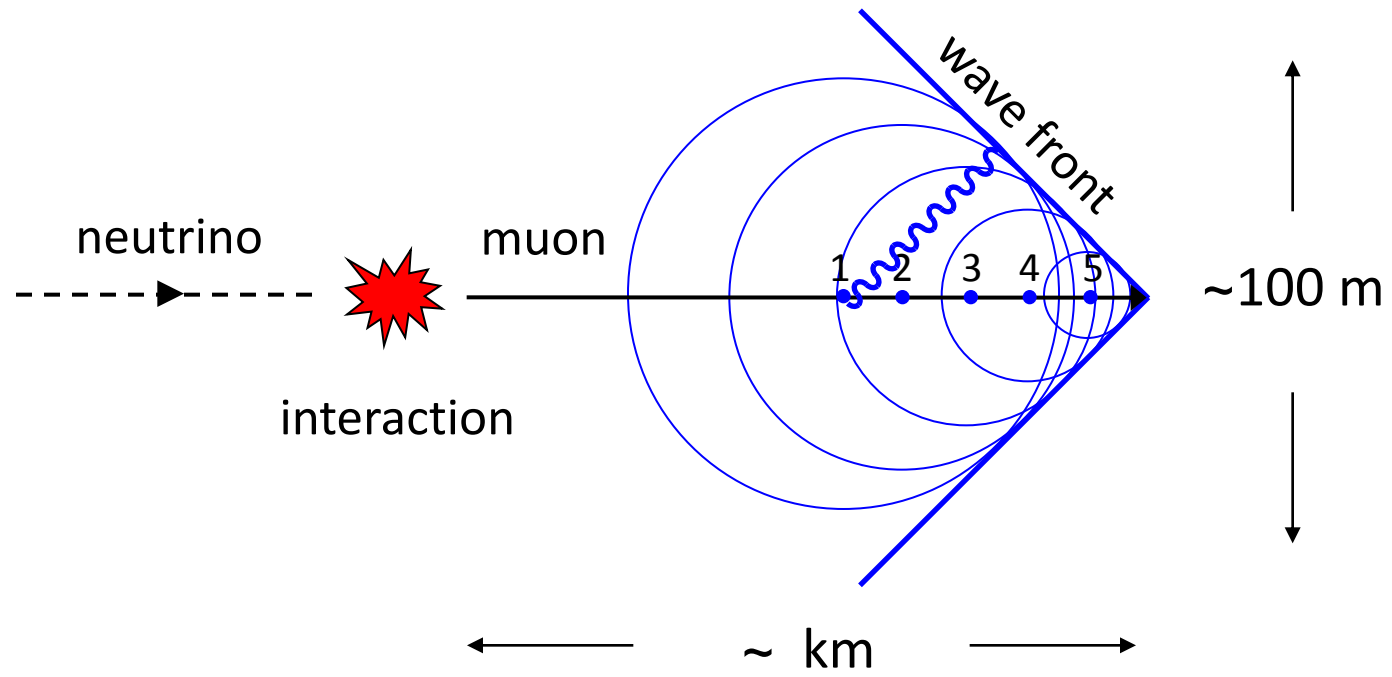
How?

1960 Markov's idea:

Seawater as interaction and detection medium

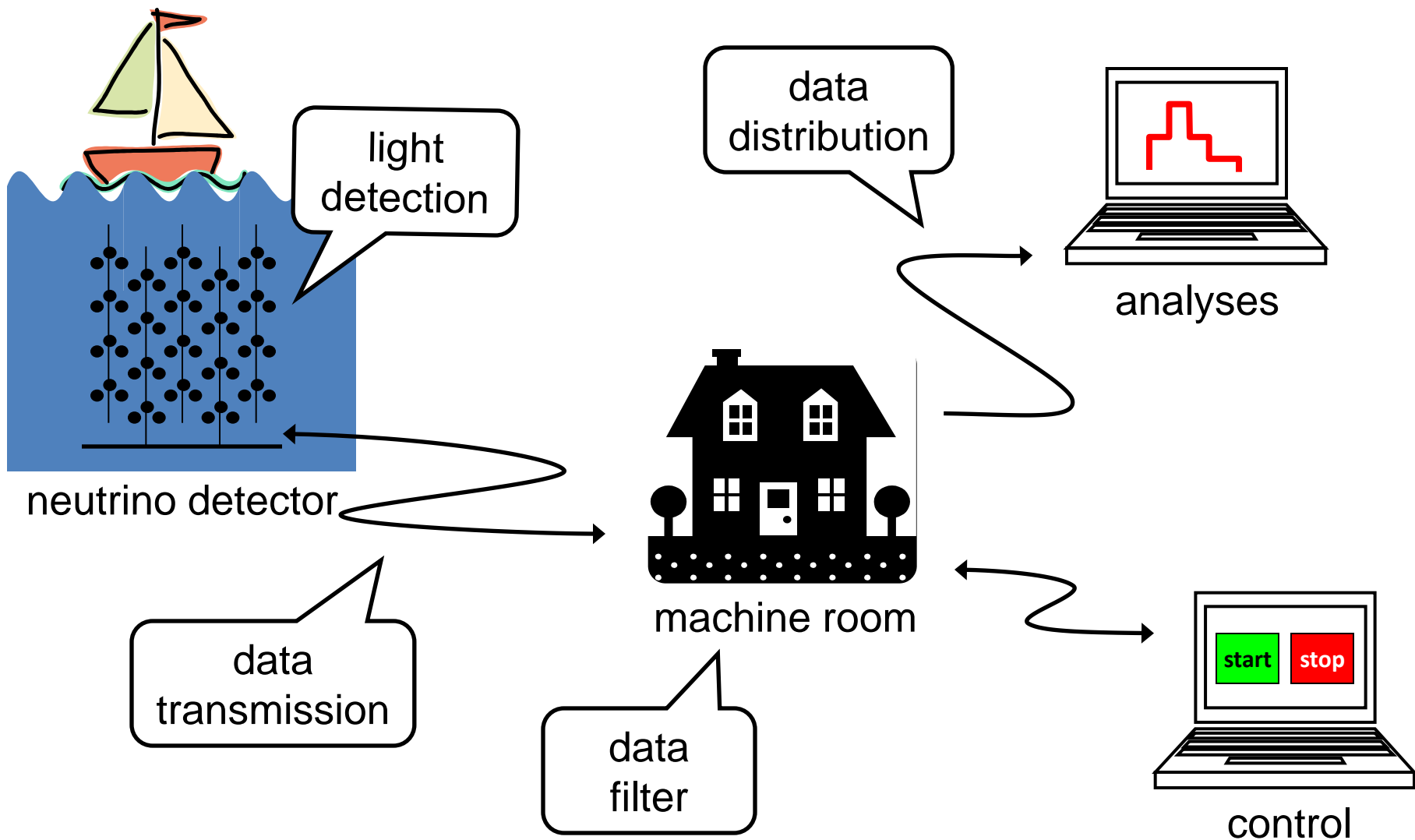
- Length muon trajectory
- Detection Cherenkov light
- Water is transparent

neutrino detection



muon travels with the speed of light (300,000 km/s)
↓
detection Cherenkov light *ns – km*

Architecture



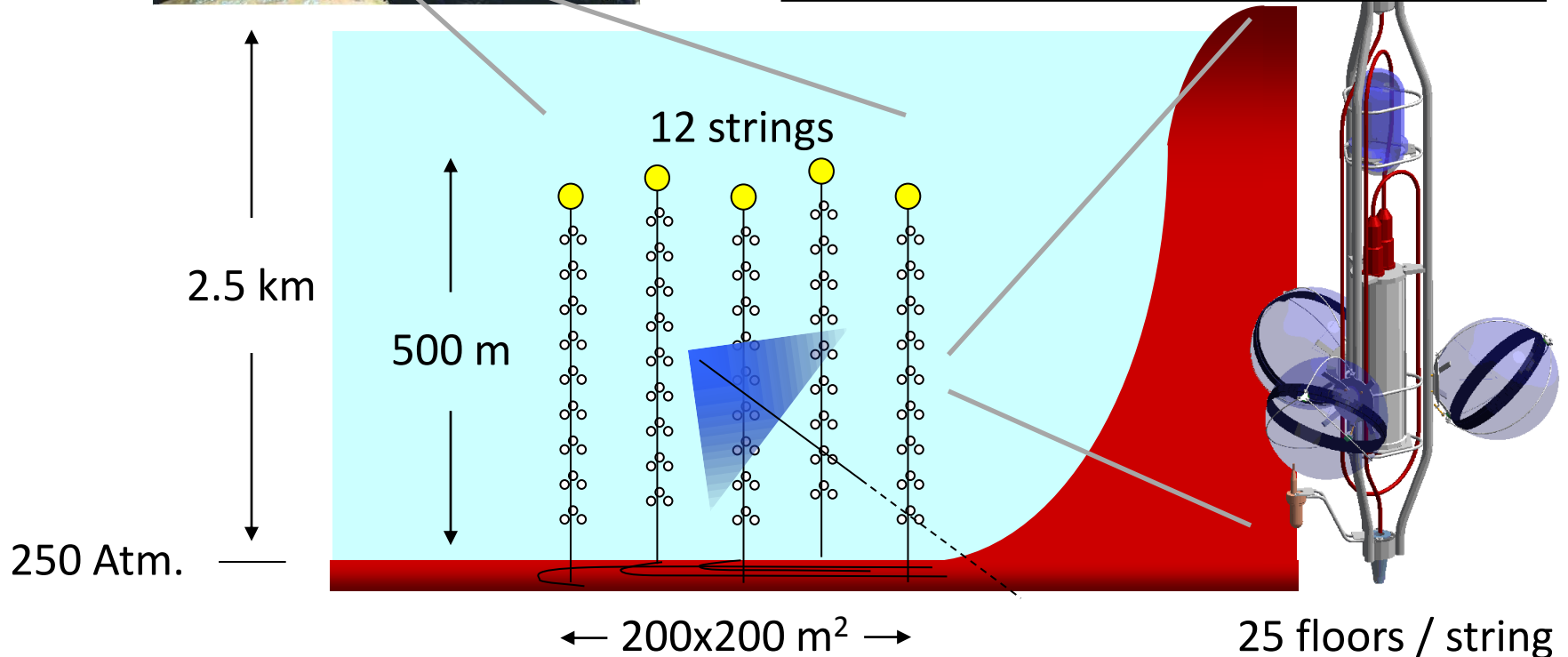
Antares

prototype neutrino telescope

Antares



- 200 persons
- 6 countries
- 40 km off the coast of Toulon
- operation 2008–2016



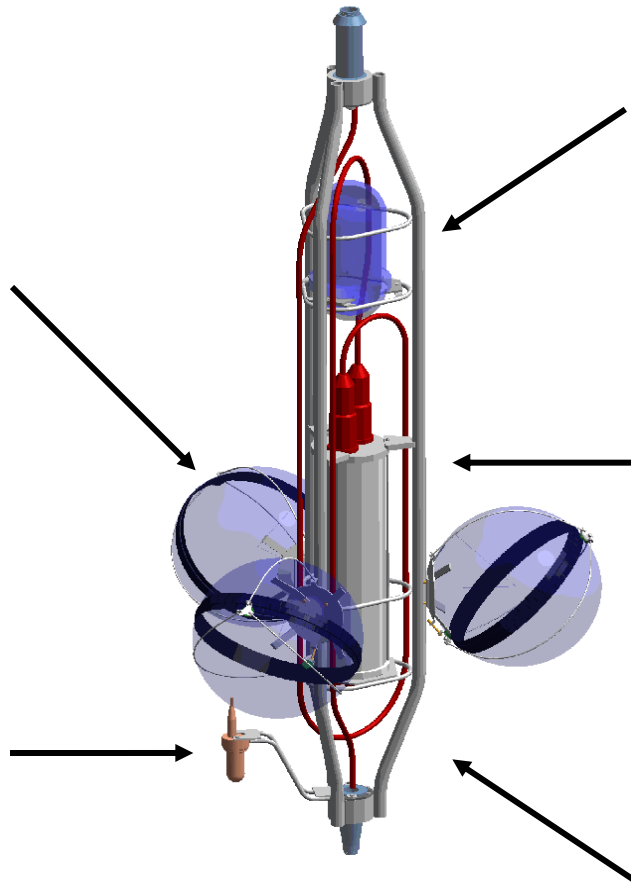
Detection unit



10" PMT
photon detection



Hydrophone
acoustic positioning



← ~1 m →

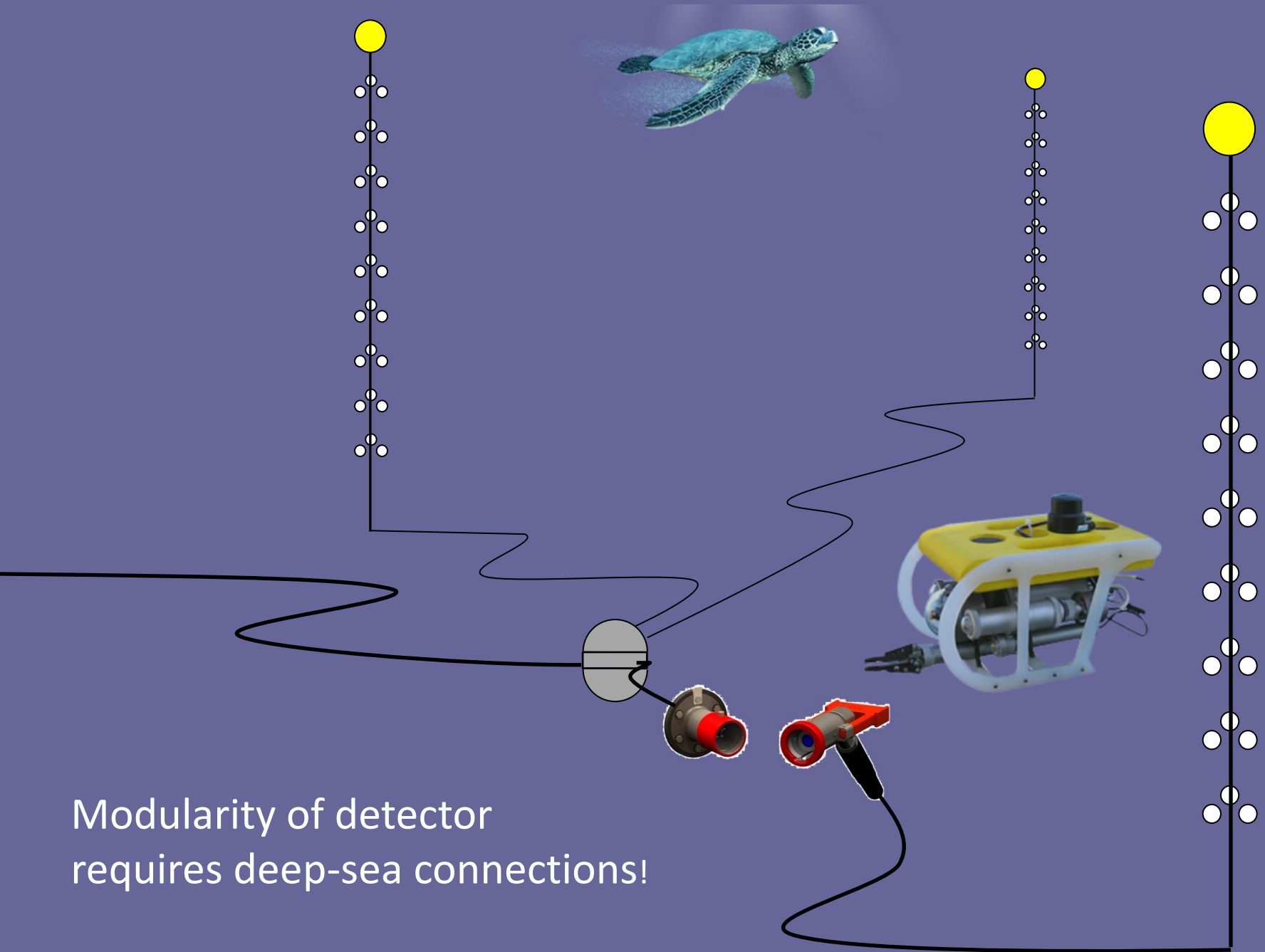


Optical beacon
timing calibration



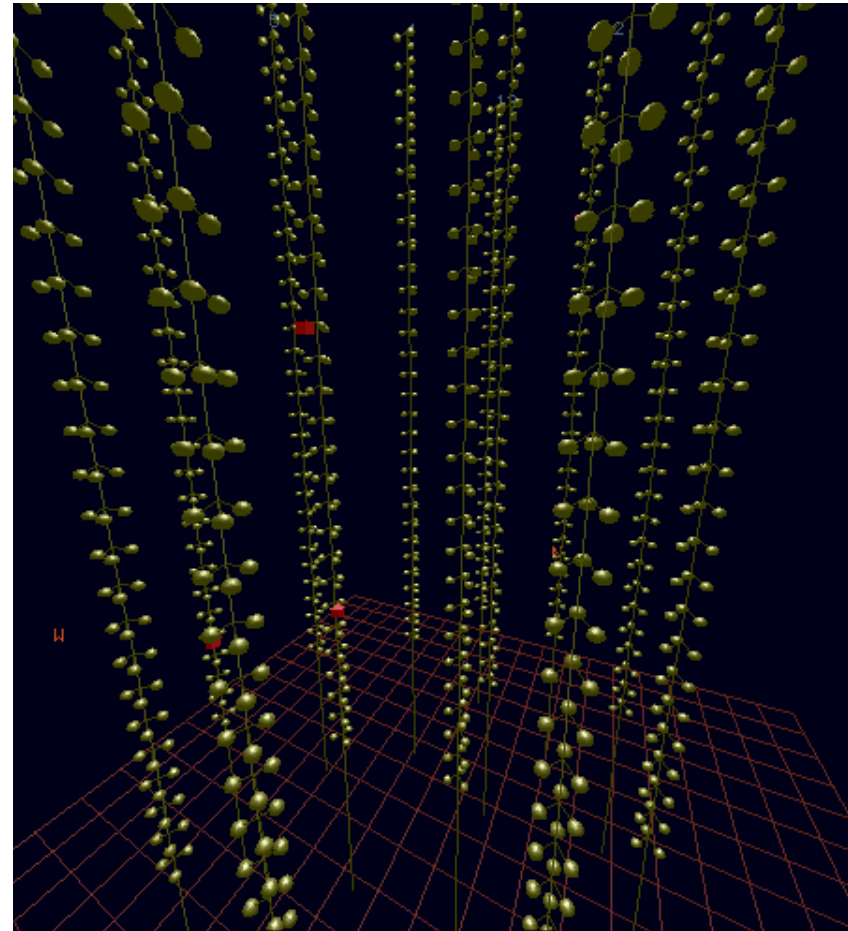
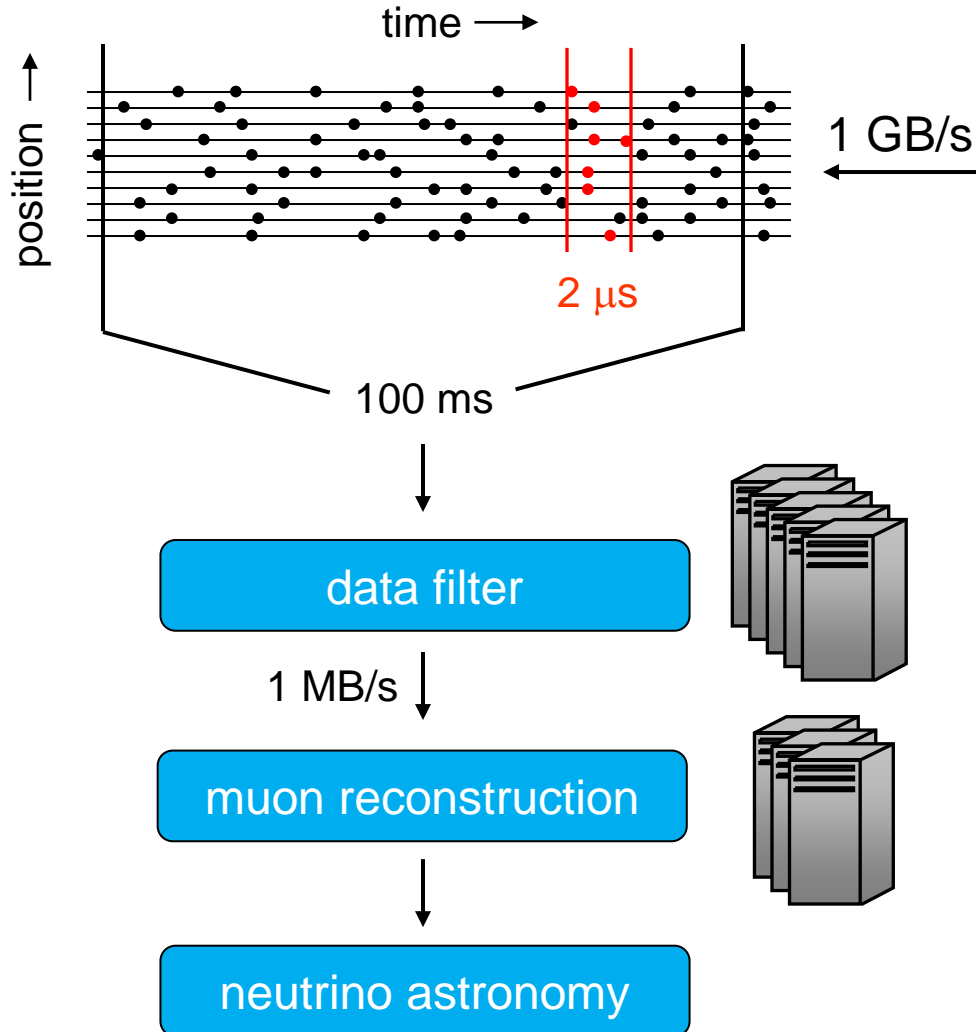
Electronics
readout

titanium frame
mechanical support

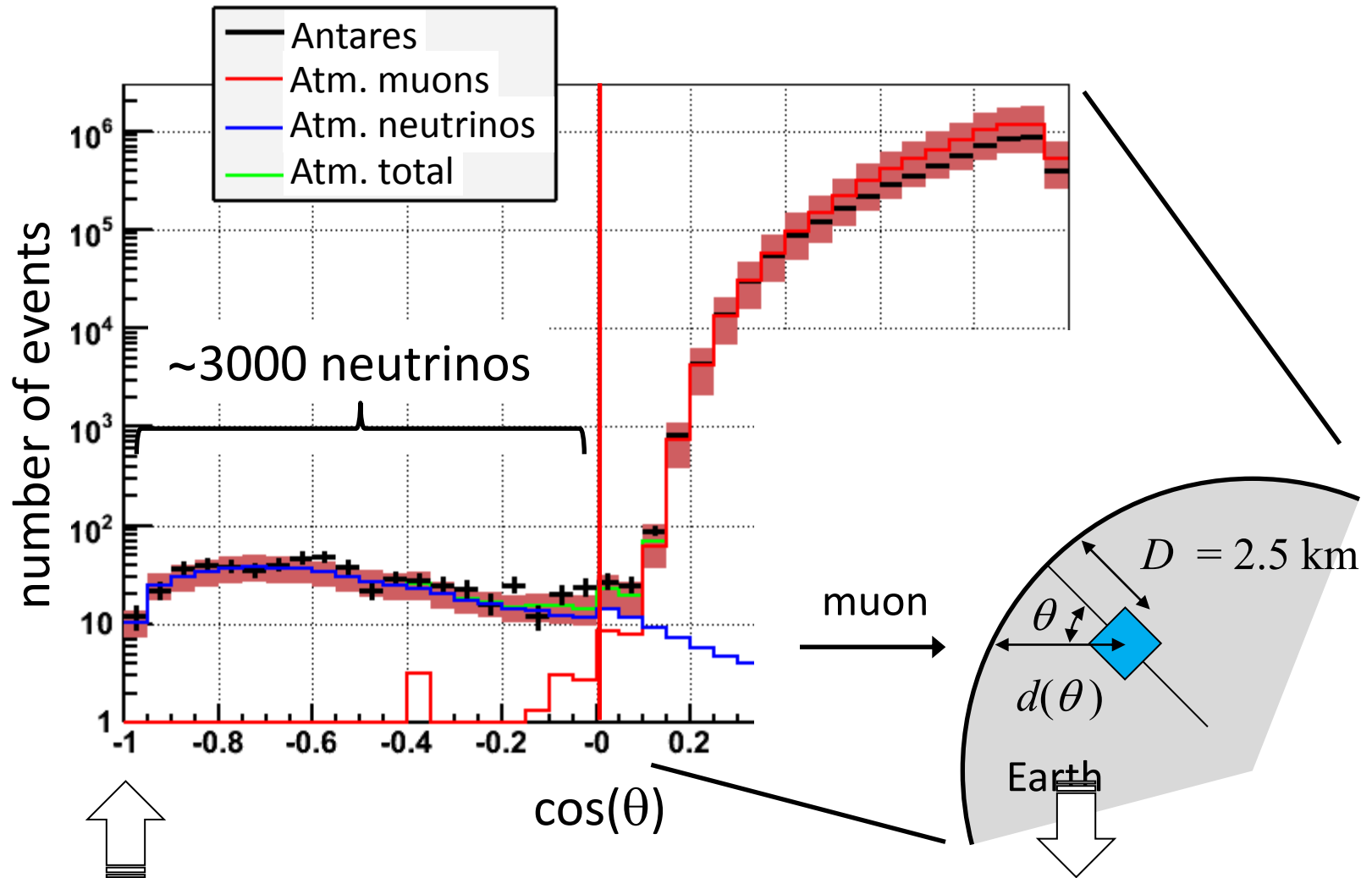


Modularity of detector
requires deep-sea connections!

All-data-to-shore



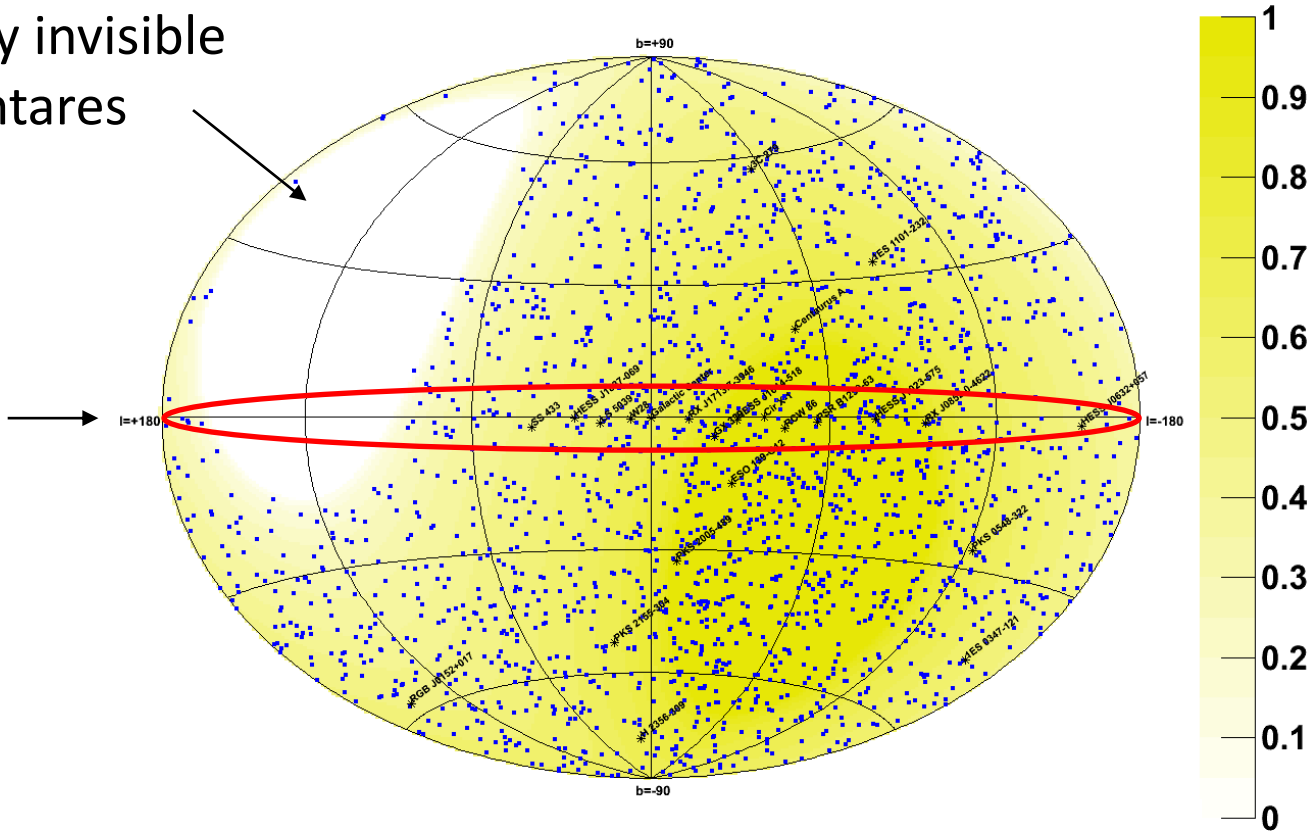
Neutrino detection



Neutrino “sky map”

part of sky invisible
to Antares

Galactic
plane



No point sources found yet

Future plans

KM3NeT: A KM³ Neutrino Telescope

Detection unit



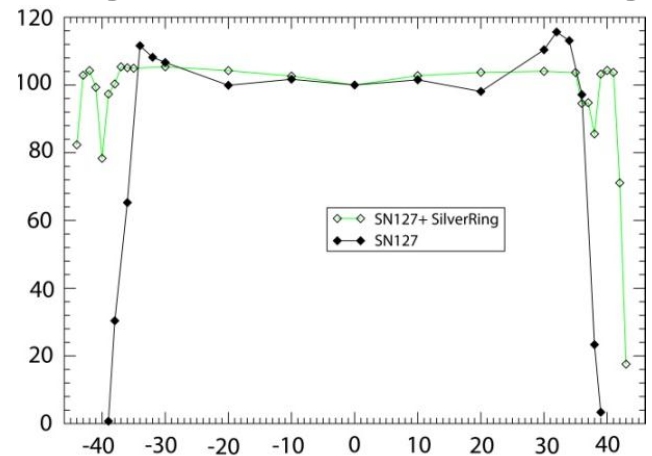
← 17 inch →

31 x 3" PMT



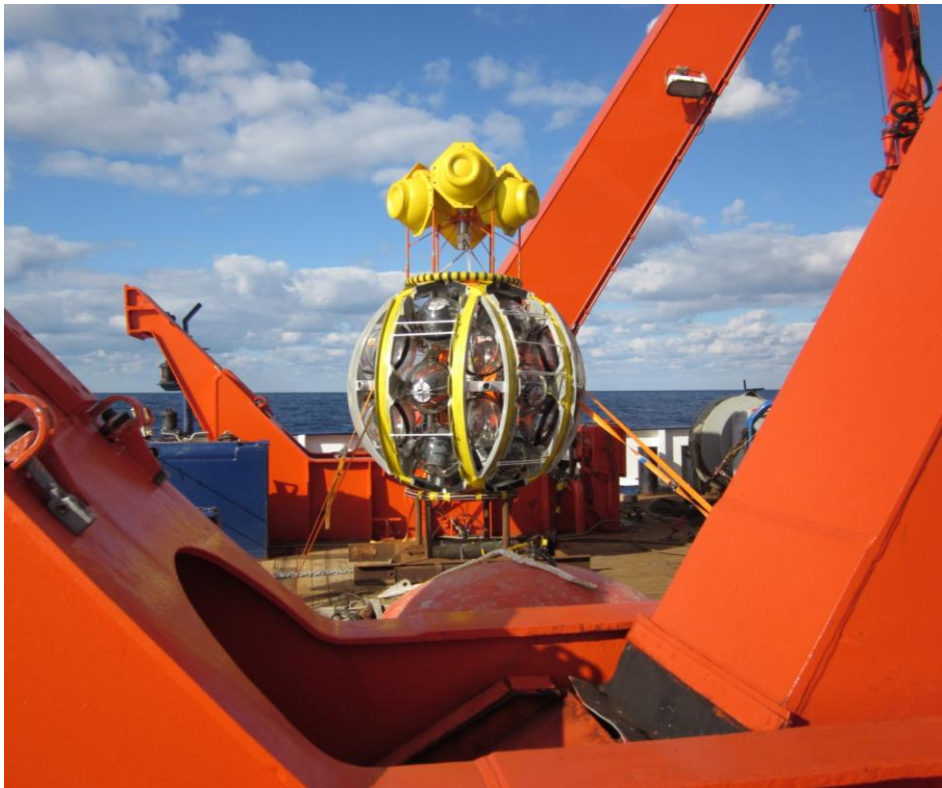
3 x 10" PMT

light concentrator ring



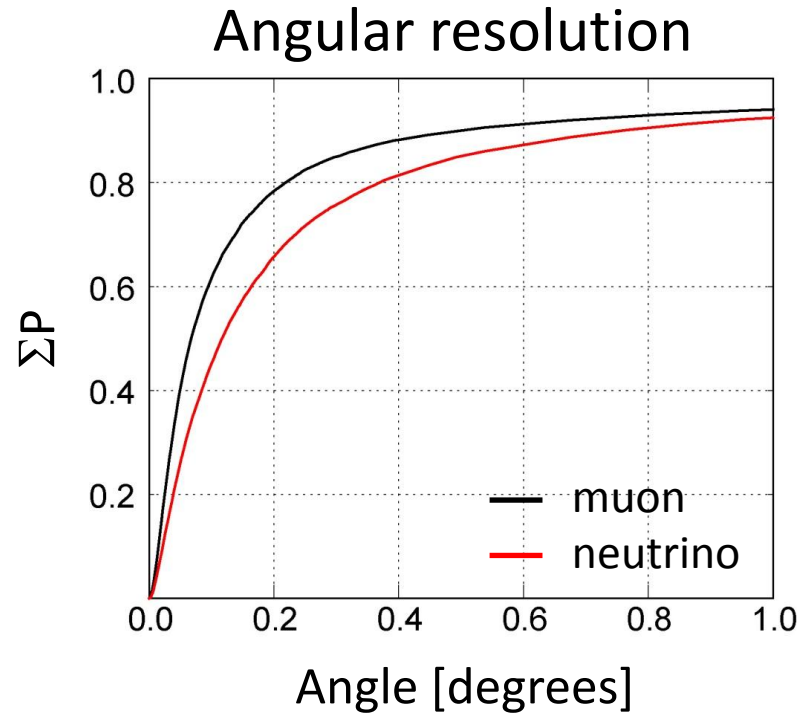
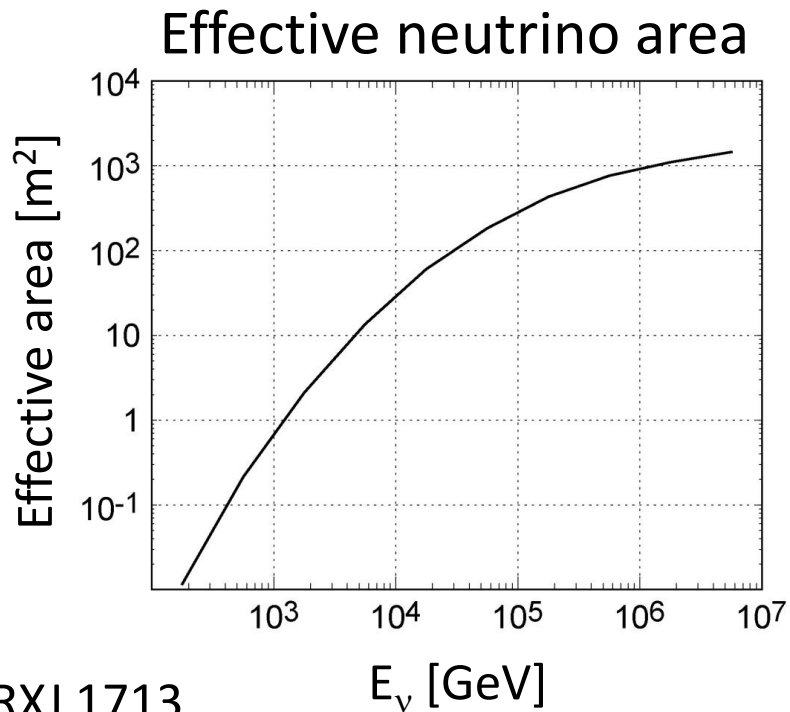
increase of photo-cathode area by 20–40%

Deployment vehicle

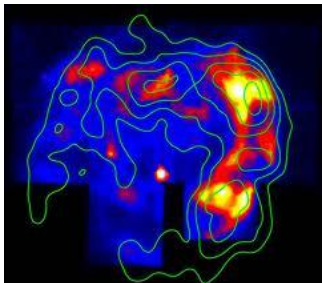


- Developed by NIOZ in the framework of the KM3NeT Design Study
- Fast mounting of strings with sensors (1 person in 2 days)
- Rapid deployment of compact object
- Autonomous unfurling

Performance

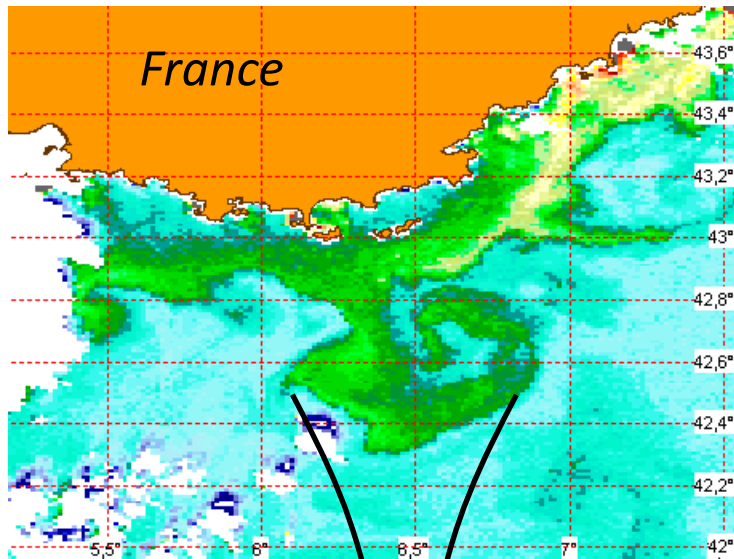


RXJ 1713



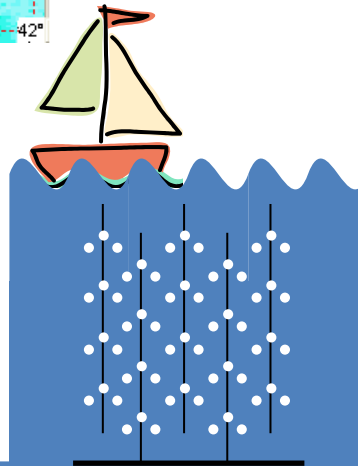
- Supernova remnant “*origin of cosmic rays*”
- 5 sigma discovery in 5 years (5/5)

Earth & Sea sciences



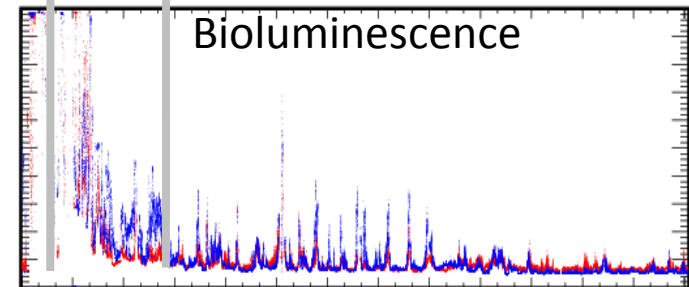
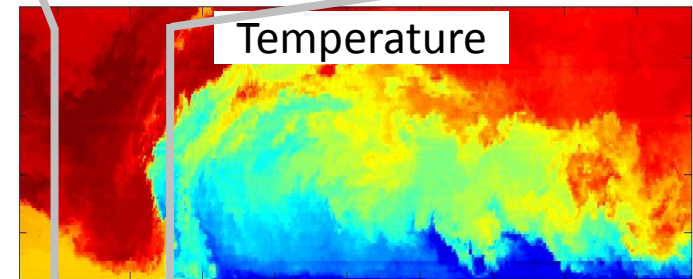
*sudden
Eddy currents*

food supply



observatory

short lived (rare) events
dominate deep-sea life
↓
permanent observatory



time profile

Summary & outlook

- Low energy neutrinos from the sun and SN1987A have been detected
- Evidence for astrophysical particle acceleration
- High energy neutrinos from other astrophysical sources?

Following the successful construction of the Antares detector as a prototype and the acquisition of start capital for KM3NeT as the future cubic kilometre detector, today neutrino astronomy is within reach.